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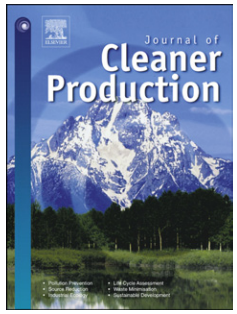

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CARBON FOOTPRINT AND EMERGY COMBINATION FOR ECO-ENVIRONMENTAL ASSESSMENT OF CLEANER HEAT PRODUCTION

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Abstract

The aim of this paper is to study via environmental indicators to which extent, replacing fossil fuel with biomass for heating is an environmentally friendly solution. The environmental impact of using biomass depends mostly on the transportation process. Authors define the notion of maximum supply distance, beyond which biomass transportation becomes too environmentally intensive compared to a fossil fuel fired heating system.

In this work a carbon footprint analysis and an emergy evaluation, has been chosen to study the substitution of wood for natural gas. The comparative study seeks to examine, via the two approaches, two heating systems: one is fired with wood, transported by trucks and the other one is fired with natural gas transported by pipelines. The results are expressed in terms of maximum supply distance of wood. In the emergy evaluation it represents the maximum supply distance permitting wood to be more emergy saving than natural gas. In the carbon footprint analysis, it represents the maximum supply distance permitting wood to be a carbon saving alternative to natural gas. Furthermore, the unification of carbon footprint and emergy evaluation permits to define, for both approaches, the minimum theoretical wood burner first law efficiency that allows, CO_2 or emergy to be saved, when there is no wood transport. In order to identify the impacts of the main parameters of the study a sensitivity analysis has been carried out.

The case study investigated in this paper shows that there is a large gap between the results. The maximum supply distances calculated via carbon footprint and emergy evaluation are about 5000 km and 1000 km respectively and the minimum theoretical wood burner efficiencies are about 5% and 54% respectively.

1. Introduction

Global warming and declining fossil fuel reserves pushed many researchers to find out alternative sources of energy. Notions of *biofuel*, *bioenergy* and *biomass* are commonly used, but in reality they can be defined in different ways. In terms of microbiology, *biomass*, synonym of *bioorganisms*, is a source for methane production (Nallathambi Gunaseelan, 1997), or hydrogen production (Ji et al, 2011). In this context, *biofuel* or *bioenergy* refers to *bioorganisms* digestion products. From energy point of view, *biomass* refers to contemporary plant matter formed by photosynthetic capture of solar energy and stored as chemical energy (Franck and Smith, 1988). As well as, Schmidt et al. (2011) consider *biomass* as forest biomass and agricultural biomass. Thus, *biofuel* or *bioenergy* can be considered as a renewable source of energy, only if the biomass harvest is replanted in the same period as it is combusted (Demirbas, 2005; Cowie et al., 2007). This is to ensure that biomass is maintained on one hand and on the other hand, new plants absorb, whilst growing, all CO_2 emitted by combustion to keep the carbon cycle in balance. Actually, only this kind of biomass ensures significant amounts of bioenergy, see (Al-Mansour and Zuwala, 2010). The review of Saidur et al. (2011) details the different applications of biomass and identifies the efficiency of each technical conversion. The most expanded conversion of biomass is combustion, which is usually used for fossil fuel substitution such as natural gas, coal or oil.

It should be underlined, that fossil fuels cannot be accepted as *bioenergy* sources since it took millions of years to transform the original *biomatter*, near the terrestrial magma (under great pressure and constant heat). On one hand, it is not possible to produce fossil fuel as fast as it is consumed. On the other hand, the carbon released by fossil fuel has been stored millions of years ago and therefore present fossil fuel combustion is increasing the CO_2 content in the atmosphere.

That is why fossil fuel substitution became a great topic for research over the last years. The studies can be classified under five group headings:

- Technical aspect which involves the improvement of the conversion systems. Stehlı´k (2009) details a review on technologies which deal with bioenergy conversion. The cleaning of the exhaust gases is also under study (Skodras et al., 2007).

- Economic aspect which evaluates the cost-effectiveness of using biomass. As such, De and Assadi (2009) and McIlveen-Wright et al. (2011) have studied the financial retrofit of a co-combustion plant (coal biomass).
- Policy actions that are required to intensify the development of biomass in energy applications. Schmidt et al. (2011) focused their work on forest biomass in association with CO_2 certifications. Mirata et al. (2005) worked on the concept of distributed economy, notably in biomass sectors.
- Criteria of sustainable biomass production. A beneficial biomass production includes low fossil fuel use, sustainable management of agriculture soils and that the biomass crops are not in competition with food crops. Hence, Mizsey and Racz (2010) have challenged bio-ethanol production versus biomass (corn) combustion per hectare, on the basis of the fossil fuel required during the global process (from cradle to the grave).
- Analysis methodology such as LCA (Salazar and Meil, 2009; Caserini et al., 2010), carbon footprint (Holden and Høyer, 2005), greenhouse gases (Poudel et al, 2012) and emergy (represents the embodied energy and can be considered as an energy footprint of a product. The fundamentals are explained by Odum (1996)). Numerous studies have been carried out to compare these analytical methods (Sebastián et al., 2011). Carraretto et al. (2004) studied via emergy analysis and life cycle assessment, the environmental impact and the pros and cons of biodiesel as alternative fuel in boilers and diesel engines. Ju and Chen (2011) calculated the CO_2 emissions of a typical biodiesel production chain and assessed the ecological performance of the production chain by means of embodied energy analysis and emergy analysis. Ulgiati and Brown (2002) evaluated the requirement for environmental services to dilute and abate process emissions of electricity production. Finally, Nilsson (1997) investigated the feasibility of using straw as a fuel in district heating plants by using energy, exergy and emergy approaches.

The substitution of biofuel for fossil fuels seems to be a great contribution to cleaner production. Particularly, because biofuels are considered as carbon-neutral, burning biofuels only emit back to the environment the CO_2 that the plants absorbed whilst growing. The production and transportation process of biofuels, however, may not be carbon-neutral and that is why, it is very important to assess the limitation of biofuel to be a carbon-saving source of energy. Thus, a sustainable economic and environmental development of biomass is intrinsically linked to a local collection area. Eriksson (2008) in a paper highlighted the impact of biomass transport on the total cost and the associated CO_2 impact. A similar study has also been applied to biofuels (von Blotnitz and Curan, 2007). In the same research area, the supply chain approach can contribute to the development of biomass applications (Lam et al., 2010; Gold and Seuring, 2011). The substitution potential of biofuels can be evaluated using footprint analysis, as they are effective methods to measure sustainability (Stöglehner, 2002). Definitions and units of environmental, social and economic footprints as well as diverse tools for footprint evaluation are presented by Čuček et al. (2012).

This work seeks to identify the environmental performance of using wood as a substitute for natural gas for producing thermal power of a small heating network. Contrary to natural gas the combustion of wood is considered as carbon neutral. So, the environmental performance of a wood fired heating system depends mostly on the mode and distance of wood transportation. An emergy evaluation and a carbon footprint analysis (Meunier, 2002) has been chosen to assess the maximum supply distance of wood. An original emergy versus carbon footprint diagram is defined to visualize the eco-environmental performance varying with the transport distance of wood. In the second part, a unification of the emergy evaluation and carbon footprint has been proposed. In the third and last part, a sensitivity analysis has been performed to determine the influence of different parameters on the maximum supply distances, calculated via the two approaches.

2. Methodology

A simplified heat production process includes heat production, fuel transportation, labor and services. To investigate properly the environmental impact and eco-efficiency of heat production, it is essential to specify the heat consumption, the performance of the heating system, the properties of the fuel, the modes of transport used for fuel supply (for example, coal can be transported by rail, wood by trucks and natural gas by pipelines, it is also possible to combine different modes of transport) and the labor and services required during the process.

The first law efficiency of the heating system has a significant impact on fuel use, since high efficiency reduces fuel consumption required to meet heating demand. A special care should be taken in choosing the type and quality of fuel, since the fuel consumption and the associated environmental impacts depend on the properties of the fuel. More especially renewable and fossil fuels must be clearly distinguished. It is also crucial to identify the means of transport, the sources of energy and the distance crossed to deliver the fuel. Finally, the environmental impairments of all labor and services needed during the process have to be taken into account.

A carbon footprint analysis and an emergy evaluation have been used to realize the eco-environmental quality assessment of two heating systems. These two environmental indicators have been chosen to cover all relevant aspects of the heat production process that may have an environmental impact. Carbon footprint analysis permits to measure the effect on the climate, in terms of the amount of CO_2 emitted during heat production, while the emergy evaluation accounts for all forms of energy and resources used in the process. Furthermore, the two approaches may be considered as complementing each other and a unification of the two indicators is envisaged. The results of the comparative study depend mainly on the following parameters (see Figure 1):

- The heat consumption Q_{th}
- The first law efficiency of the heating system η_b
- The low heating value of the fuel LHV_f
- The fuel consumption Q_f
- The supply distance of fuel D
- The energy needed for fuel transportation Q_e
- And the energy consumed for labor and services $Q_{l\&s}$

For obtaining meaningful and significant results, it is very important to define the framework of the comparative study such as the time horizon and the boundaries of the heat production process.

Figure 1. Simplified process diagram of heat production

3. Case study

This paper proposes a comparative study between a wood fired heating system and a natural gas fired heating system. The aim is to identify the environmental performance and eco-efficiency of using biomass as a substitute for fossil fuels for heat production. As a concrete example, the ecological sustainability of a project launched in 2010 has been analyzed, which consists of building a central wood-fired heating plant in the district of Chantrerie (Nantes-France). The aim is to replace local natural gas heating units, in total, 25 natural gas boilers providing the space heating of 5 establishments (4 institutions of higher education and a laboratory for veterinary tests) covering an area of 120 000 m², which corresponds to an annual thermal consumption of about Q_{th} = 42 800 GJ_{th} (average annual heat consumption of the campus over the past five years).

To provide a consistent basis for comparing the two heating systems, the same steps of heat production have been considered to assess the eco-environmental performance of each of them. In the calculations, the construction of the two plants and maintenance work on the two heating systems are not taken into account. However the fuel production and transportation, labor and services required to operate each of the two heating systems have been accounted for. In the case of the natural gas fired heating system, the boiler is directly supplied by pipelines and there is no significant labor or services required to make the automatic system work. In the case of the wood fired heating system, the wood is transported by trucks. Human labor is needed for wood supply, ash collection and functioning of the boiler. The system diagram and the CO_2 emissions of heat production via both a natural gas heating unit and a wood-fired heating plant are detailed respectively in Figure 2 and Figure 3.

It has to be mentioned that upstream emission factors have been used to estimate the CO_2 emissions of production and transportation for both diesel and natural gas. Wood combustion cannot be considered as carbon neutral unless the overall stock of forest is maintained. Thus an upstream emission factor of wood has been used to calculate the CO_2 emissions of producing controlled forest biomass. The same approach has been applied in choosing the transformities for the emergy evaluation.

Figure 2. System diagram of heat production via a natural gas heating system

Figure 3. System diagram of heat production via a wood fired heating system

Table 1

Parameters of the study

3.1. Model

In the general case, the annual fuel consumption q_f [kg] of a boiler is given by:

$$q_f = \frac{Q_{th}}{LHV_f * \eta_b} \quad (1)$$

Where, Q_{th} [MJ] is the average annual heat consumption, LHV_f [MJ/kg] is the low heating value of the fuel and η_b is the first law efficiency of the boiler.

In the case of a wood boiler, the low heating value of wood at constant pressure LHV_w is given by the Equation (Telmo and Lousada, 2011):

$$LHV_w = \frac{LHV_w(0\%) * (100 - M)}{100} - 0.02443 * M \quad (2)$$

Where, $LHV_w(0\%)$ is the low heating value of dry wood (moisture-free) and M is the moisture content of wood.

Thus, the annual wood consumption of the boiler q_w [kg] is:

$$q_w = \frac{100 * Q_{th}}{[(LHV]_w(0\%) * (100 - M) - 2.443 * M) * \eta_w} \quad (3)$$

Where, η_w is the first law efficiency of the wood boiler.

In the case of natural gas boiler, the annual natural gas consumption Q_{ng} [MJ] is given by:

$$Q_{ng} = \frac{Q_{th}}{\eta_{ng}} \quad (4)$$

Where, η_{ng} is the first law efficiency of the natural gas boiler.

Carbon footprint analysis:

The carbon footprint analysis permits to quantify all the CO_2 emissions of the natural gas and wood fueled heating systems.

- The annual CO_2 emission of the natural gas fueled heating system $CO_2^{ng_b}$ [kgCO_2] is given by:

$$CO_2^{ng_b} = Q_{ng} * \left(EF_{up_{ng}} + EF_{comb_{ng}}\right) \quad \textbf{(5)}$$

Where, $EF_{up_{ng}}$ is the upstream emission factor and $EF_{comb_{ng}}$ is the combustion emission factor of natural gas and Q_{ng} [MJ] is the annual consumption of natural gas.

- The annual CO_2 emission of the wood fueled heating system $CO_2^{W_b}$ [kgCO_2] is given by:

$$CO_2^{W_b} = CO_2^{W_{tr}} + CO_2^{a_{tr}} + CO_2^{e_{tr}} + CO_2^{W_{up}} \quad \textbf{(6)}$$

Where, $CO_2^{W_{tr}}$ [kgCO_2] is the CO_2 emissions of wood transportation, $CO_2^{a_{tr}}$ [kgCO_2] is the CO_2 emissions of ash collection, $CO_2^{e_{tr}}$ [kgCO_2] is the CO_2 emissions of the home-to-work travel of the employees and $CO_2^{W_{up}}$ [kgCO_2] is the upstream emissions of wood.

$$CO_2^{W_{tr}} = ND * D * \left(EF_{up_d} + EF_{comb_d}\right) * \varepsilon * \frac{M_{CO_2}}{M_C} * FC^{W} * (1 + \gamma^{W}) \quad \textbf{(7)}$$

$$CO_2^{a_{tr}} = NC * d * \left(EF_{up_d} + EF_{comb_d}\right) * \varepsilon * \frac{M_{CO_2}}{M_C} * FC^{a} * (1 + \gamma^{a}) \quad \textbf{(8)}$$

$$CO_2^{e_{tr}} = D_e * \left(EF_{up_d} + EF_{comb_d}\right) * \varepsilon * \frac{M_{CO_2}}{M_C} * FC^{v} \quad \textbf{(9)}$$

$$CO_2^{w_{up}} = q_w * LHV_w * EF_{w_{up}} \quad \textbf{(10)}$$

Where, ND is the number of wood deliveries during the heating period $ND = \frac{q_w}{C_{w_{tr}\max}}$, $C_{w_{tr}\max}$ is the load capacity of the truck used for wood delivery), D [km] is the transport distance of wood, EF_{up_d} is the upstream emission factor of diesel, EF_{comb_d} is the combustion emission factor of diesel, ε is the oxidation factor, $\frac{M_{CO_2}}{M_C}$ is the ratio of the molecular weight of CO_2 to the molecular weight of carbon, the ratio of average fuel consumption of the truck used for wood supply without charge FC^{w_0} to average fuel consumption of the truck with charge FC^w is $\gamma^w = \frac{FC^{w_0}}{FC^w}$, NC is the number of ash collection ($NC = \frac{\alpha * q_w}{C_{a_{tr}\max}}$, α is the ash content and $C_{\max}(a_{tr})$ is the load capacity of the truck used for ash collection), d is the distance crossed by the trucks to remove ash, FC^a is the fuel consumption of the truck used for ash collection, $\gamma^a = \frac{FC^{a_0}}{FC^a}$ is the ratio of average fuel consumption of the truck used for ash collection with charge FC^{a_0} to average fuel consumption of the truck charge FC^a, D_e is the annual distance travelled by the employees to get to work and back again, FC^v is the fuel consumption of a passenger car and $EF_{w_{up}}$ is the upstream emission factor of wood. The upstream and combustion emission factors of natural gas, diesel and wood are given in Table 2.

The carbon saving performance of the wood fueled heating system depends on the supply distance of wood and the load capacity of the truck. Hence, for a fixed load capacity $C_{\max}(w_{tr})$, the maximum transport distance $D_{\max}^{cf}$ allowing wood to be a carbon saving alternative to natural gas is given by:

$$CO_2(ng_b) = CO_2(w_b)\ (D_{\max}^{cf}) \quad (11)$$

Thus, according to Equation (5) and (6):

$$D_{\downarrow}\max^{\uparrow}cf = ([\![CO]\!]_{\downarrow}2^{\uparrow}(ng_{\downarrow}b) - [\![CO]\!]_{\downarrow}2^{\uparrow}(a_{\downarrow}tr) - [\![CO]\!]_{\downarrow}2^{\uparrow}(e_{\downarrow}tr) - [\![CO]\!]_{\downarrow}2^{\uparrow}(w_{\downarrow}up))/(ND$$

Table 2

Emission factors

Emergy evaluation:

The emergy evaluation permits to assess the emergy flow of the natural gas and wood fueled heating systems.

- The annual emergy flow of the natural gas fueled heating system E_{ng_b} [sej] is given by:

$$E_{ng_b} = Q_{ng} * [\![(\tau]\!]_{ng} + \tau_{ng_{tr}}) \qquad (13)$$

Where, τ_{ng} is the solar transformity of natural gas, $\tau_{ng_{tr}}$ is the solar transformity of natural gas transport.

- The annual emergy flow of the wood fueled heating system E_{w_b} [sej] is given by:

$$E_{w_b} = E_w + E_{w_{tr}} + E_{a_{tr}} + E_{e_{tr}} + E_{\mathrm{hl}} \qquad (14)$$

Where, E_w [sej] is the emergy flow of wood, $E_{w_{tr}}$ [sej] is the emergy flow of wood transportation, $E_{a_{tr}}$ [sej] is the emergy flow of ash collection, $E_{e_{tr}}$ [sej] is the emergy flow of the home-to-work travel of the employees and E_{hl} is the emergy flow of human labor [sej].

$$E_w = q_w * LHV_w * \tau_w \qquad (15)$$

$$E_{w_{tr}} = ND * D * LHV_d * \tau_d * FC^w * (1 + \gamma^w) \qquad (16)$$

$$E_{a_{tr}} = NC * d * LHV_d * \tau_d * FC^a * (1 + \gamma^a) \quad (17)$$

$$E_{e_{tr}} = D_e * LHV_d * \tau_d * FC^v \quad (18)$$

$$E_{hl} = h_w * \tau_{hl} \quad (19)$$

Where, τ_w is the solar transformity of wood, LHV_d is the low heating value of diesel, τ_d is the solar transformity of diesel, τ_{hl} is the solar transformity of human labor and h_w is the number of hours worked by the employees. The solar transformities of natural gas, natural gas transportation, wood, diesel and human labor are listed in Table 3.

From the emergy point of view, using wood as fuel is less environmentally intensive than natural gas when the emergy flow of the natural gas fueled heating system E_{ng_b} is greater than the emergy flow of the wood fueled heating system E_{w_b}. As E_{w_b} depends on the distance crossed by the trucks which supply the boiler with wood, for a fixed load capacity $C_{max}^{(w_{tr})}$, the maximum possible supply distance D_{max}^{E} permitting wood fuel to be emergy saving compared to natural gas is given by:

$$E_{ng_b} = E_{w_b}\left(D_{max}^{E}\right) \quad \mathbf{(20)}$$

Thus, according to Equation (13) and (14):

$$D_{max}^{E} = (E_{ng_b} - E_w - E_{a_{tr}} - E_{e_{tr}} - E_{hl})/(ND * LHV_d * \tau_d * FC^w *$$

Table 3

Solar transformities

3.2. Discussion

In Table 1, the load capacity of the trucks for wood delivery $C_{max}^{(w_{tr})}$, the corresponding fuel consumption FC^w, the low heating value of wood LHV_w, the moisture content of wood M and the efficiency of the wood boiler η_w have been defined in value ranges, which permits to realize the sensitivity analysis of these parameters (for more details see Appendix A). In addition, it should be pointed out that LHV_w, M and η_w are related in Equation (3) and that the fuel consumption varies with the load capacity of the truck.

Carbon footprint versus emergy evaluation:

Comparing the results of the two approaches, it must be noted that, as illustrated in Figure 4, the maximum transport distance of wood calculated via carbon footprint $D_{\max}^{cf}$ is nearly five times longer than the maximum transport distance calculated via emergy evaluation $D_{\max}^{E}$. These results indicate that the environmental impact of using wood fuel for heating cannot be effectively evaluated based solely on its CO_2 emissions. Many other factors affect the environmental performance of the process and that is why an emergy evaluation is much more appropriate since emergy measures all forms of energy which have been used or transformed to make a product or service. The corresponding emergy flows of the two heating systems are given in Tables 4 and 5. The CO_2 emissions are calculated in Tables 6 and 7.

Table 4

Emergy flows from the natural gas fired heating system

Table 5

Emergy flows from the wood fired heating system

Table 6

CO_2 emissions from the natural gas fired heating system

Table 7

CO_2 emissions from the wood fired heating system

Figure 4. Maximum distance calculated via emergy evaluation and carbon footprint

In order to compare and visualize the distance limitations of emergy evaluation and carbon footprint, a specific graph has been used, in which (see Figure 5):

- The x-axis indicates the difference between the emergy flows of the natural gas fired heating system and the wood fired heating system.
- The y-axis represents the difference between the CO_2 emissions of the natural gas fired heating system and the wood fired heating system.

The graph is divided into four quadrants. The first one represents supply distances permitting CO_2 and emergy savings, the second one represents supply distances which permits CO_2 savings but are too emergy intensive, the third one represents supply distances which are CO_2 and emergy intensive and finally the fourth one represents supply distances which are emergy saving but CO_2 intensive.

In the case illustrated in Figure 5, the x- and y-axis are respectively defined as follows:

$$\Delta E(D)[sej] = E_{ng_b} - E_{w_b}(D)$$

$$\Delta CO_2(D)[\mathbf{kgCO_2}] = CO_2^{ng_b} - CO_2^{w_b}(D)$$

Three different categories of supply distances can be observed: those accepted by emergy evaluation and carbon footprint, those exceeding distance limitation of emergy evaluation but accepted by carbon footprint and finally those which exceed the distance limitation of the two approaches. The intersections of the straight line with the x-axis and the y-axis correspond, respectively, to $[D]_{max}^{E}$ and $[D]_{max}^{cf}$, illustrated in Figure 4.

Figure 5. Eco-environmental performance varying with supply distances

3.3. Unification of carbon footprint and emergy evaluation

For a better understanding and interpretation of the large discrepancy between the results of the emergy evaluation and the carbon footprint, the possibility of a relationship between the two approaches has been investigated.

According to Equation (12) and (21) the distance ratio $(D_{max}^{E})/(D_{max}^{cf})$ can be expressed as:

$$(D_{max}^{E})/(D_{max}^{cf}) = K * ((\eta_w - \eta_{min}^{E})/(\eta_w - \eta_{min}^{cf}))$$

Where, K , η_{min}^{E} and η_{min}^{cf} are defined as follows:

$$K = \frac{\left(EF_{up_d} + EF_{comb_d}\right) * \varepsilon * \frac{M_{CO_2}}{M_C}}{LHV_d * \tau_d},$$

$$\eta_{min}^{E} = (Q_{th} * (\alpha/(C_{max}^{(a_{tr})} * LHV_w) * d * LHV_d * \tau_d * FC^{a} * (1 + \gamma^{a}$$

$$\eta_{min}^{cf} = \frac{Q_{th}\left(* \alpha \left(\frac{\square}{C\left(\max_{\square}^{a_{tr}} * LHV_w\right)} * d * \left(EF_{up_d} + EF_{comb_d}\right) * \varepsilon * \frac{M_{CO_2}}{M_C} * FC^{a} * (1 + \gamma^{a}) + EF_{w_{up}} \right)\right)}{},$$

It can be seen that, in the case of this study, the ratio $(D_{max}^{E})/(D_{max}^{cf})$ varies only with the low heating value of wood LHV_w and the efficiency of the wood boiler η_w, since all the other parameters are fixed. This means that the ratio $(D_{max}^{E})/(D_{max}^{cf})$ is constant for any wood fired heating system where the efficiency of the boiler η_w and the low heating value of the wood LHV_w are given. In addition, it permits to deduce directly D_{max}^{cf} from D_{max}^{E} and vice versa (see Figure 6). This points to the fact that the carbon footprint method can be considered as a part of emergy evaluation method, since it only measures the CO_2 emissions of the system while emergy evaluation considers all the energy required directly and indirectly by the system. Furthermore, it should be noticed that for a wood boiler efficiency η_w lower than η_{min}^{E}, D_{max}^{E} becomes negative. It means that from an emergy point of view, substitution of wood for natural gas is no longer sustainable. Similarly, for a wood boiler efficiency η_w lower than η_{min}^{cf}, D_{max}^{cf} becomes negative and hence, substitution of wood for natural gas is no longer carbon saving.

Figure 6. The distance ratio varying with the efficiency of the wood boiler

3.4. Sensitivity analysis

The following sensitivity analysis consists of identifying the impacts of different parameters such as the efficiency of the wood boiler, the low heating value of wood, the load capacity of trucks used to transport wood and finally the distance crossed to remove ash.

Impact of wood boiler efficiency:

According to Equation (12) and (21), for a fixed load capacity $C_{max}^{(w_{tr})}$ and low heating value of wood LHV_w the variation of D_{max}^{cf} and D_{max}^{E} with the wood boiler efficiency are given by:

$$(\partial D_{max}^{cf})/(\partial \eta_w) = (CO_2^{(ng_b)} - CO_2^{(e_{tr})})/(Q_{th}/(C_{max}^{(w_{tr})} * LHV$$

$$(\partial D_{max}^{E})/(\partial \eta_w) = (E_{(ng_b)} - E_{(e_{tr})} - E_{hl})/(Q_{th}/(C_{max}^{(w_{tr})} * LHV_w) * L$$

Since $(\partial D_{max}^{cf})/(\partial \eta_w)$ and $(\partial D_{max}^{E})/(\partial \eta_w)$ are positive constants, the maximum distances D_{max}^{cf} and D_{max}^{E} are, as illustrated in Figure 7, linear increasing functions of wood burner efficiency. According to Equation (1), the higher the efficiency of the burner the lower the wood consumption to provide heat demands for the campus and therewith greater distances are acceptable for wood supply. The intersection of the x-axis with the line of maximum supply distances calculated via emergy evaluation represents the minimum theoretical wood burner efficiency η_{min}^{E} that allows emergy to be saved.

Figure 7. Maximum distances varying with efficiency of wood burner

Impacts of low heating value of wood:

According to Equation (12) and (21), for a fixed load capacity $C_{max}^{(w_{tr})}$ and wood boiler efficiency η_w the variation of D_{max}^{cf} and D_{max}^{E} as a function of low heating value of wood are given by:

$$\partial D_{max}^{cf}/\partial LHV_w = (CO_2^{(ng_b)} - CO_2^{(e_{tr})} - (Q_{th} * EF_{(w_{up})}$$

$$\partial D_{max}^{E}/\partial LHV_w = (E_{(ng_b)} - E_{(e_{tr})} - E_{hl} - (Q_{th} * \tau_w)/\eta_w)/(Q_{th}/(C_{max}$$

Since $\partial D_{max}^{cf}/\partial LHV_w$ and $\partial D_{max}^{E}/\partial LHV_w$ are positive constants, the maximum distances D_{max}^{cf} and D_{max}^{E} are, as shown in Figure 8, linear increasing functions of low heating value of wood. In reality, as shown in Equation (2), high moisture content of wood M lowers the heat value LHV_w and hence a higher quantity of wood is needed to provide the heat demand. The rise of wood consumption implies a higher number of wood deliveries ND and shorter acceptable supply distances of wood.

Figure 8. Maximum distances varying with low heating value of wood

Impacts of load capacity of trucks:

For a given wood consumption, the increase of $C_{max}^{(w_{tr})}$ reduces the number of wood deliveries ND and according to Equation (12) and Equation (21), greater distances for supplying the burner with wood are possible. Thus, as shown in Figure 9, the maximum accepted supply distances of wood, D_{max}^{cf} and D_{max}^{E} increase with the load capacity of truck $C_{max}^{(w_{tr})}$.

Figure 9. Maximum distances varying with load capacity of trucks

Impact of distance crossed to remove ash

The ash quantity during the heating period is negligible compared to the wood consumption Q_w of the burner (α is about 2%), that is why the distance crossed to remove ash does not affect considerably the calculation of acceptable wood supply distances $D_{\downarrow}\mathrm{max}^{\uparrow}cf$ and $【D】_{\downarrow}\mathrm{max}^{\uparrow}E$.

Uncertainty analysis of emission factors and transformities:

Emission factors and transformities are very sensitive to several factors (time, region, resources, production process, utilization…) and it is quite difficult to find out the appropriate value that has to be used. That is why the relative error for 10% of change of all the emission factors and transformities , used in this work, has been calculated, see Table 8 and Table 9.

The relative error is defined as:

$$\sigma_x = \frac{\Delta D}{D_0} = \frac{\left|\frac{\partial D}{\partial x} * (x - x_0)\right|}{D_0}$$

With:

$$\begin{cases} x \in \{EF_i; \tau_j\};\ i = \{Natural\ gas, wood, diesel\}, j = \{Natural\ gas, wood, diesel, human\ labor\} \\ x - x_0 = 10\% * x_0 \end{cases}$$

Table 8

Relative errors of emission factors

Table 9

Relative errors of transformities

It can be noticed that for coherent results of carbon footprint analysis the emission factors of fossil fuel should be carefully chosen, as they are important CO_2 creators. To realize a meaningful emergy evaluation special care must be taken in choosing the transformities of the fuel used for heat production, whether fossil fuel or biomass.

4. Conclusion

This paper discusses the feasibility conditions of using biomass as a substitute for fossil fuel. Authors used a carbon footprint analysis and emergy evaluation to assess the maximum supply distance of biomass that permits biomass to be, according to the approach, a CO_2 or emergy saving alternative to fossil fuel.

As the emergy evaluation takes into account both the impact of fossil fuel as well as carbon footprint, the unification of the two approaches has been applied. This permits to define, for each of the two approaches, the minimum theoretical wood burner efficiency that allow, according to the approach, CO_2 or emergy saving, when there is no wood transport (the wood burner is constructed in the forest). In addition, it permits to relate, for any wood boiler with known characteristics, the maximum acceptable supply distances of the two approaches $D_{\max}^{cf}$ and $D_{\max}^{E}$. This makes it possible to deduce the maximum supply distance of one approach from the other.

In the case study, a project launched in 2010 has been analyzed, which consists of building a central wood fired heating plant in the zone of Chantrerie (Nantes-France), to replace local natural gas heating units. The results show that the maximum supply distance and the minimum theoretical wood burner first low efficiency calculated via carbon footprint are respectively about 5000 km and 5%. Whereas the maximum supply distance and the minimum theoretical wood burner first low efficiency calculated via emergy evaluation, are about 1000 km and 54%. These results do not surprise because contrary to carbon footprint, which measures only the CO_2 emissions of the process, the emergy concept is based on the principle of memorizing all the available energy that has been required directly or indirectly to make a product or service.

The sensitivity analysis reveals that the eco-environmental efficiency of wood as a substitute for natural gas depends mainly on the performance of the heating system (efficiency of the wood boiler), the quality of wood (moisture content of wood) and the fuel consumption of the trucks transporting the wood. The uncertainty analysis of the emission factors and transformities indicates that special care should be taken in choosing the emission factors of fossil fuels (in this case natural gas and diesel) and the transformities of the fuels used to fire the heating system (whether it is fossil fuel or biomass).

The methodology proposed in this paper is appropriate to study the environmental impacts of all types of fossil fuel substitution by biomass. For finer judgments, however, one must not lose sight of the generic advantages and disadvantages of using biomass instead of fossil fuels. Biomass represents a locally produced inexhaustible source of energy, emphasizing job creation and permitting countries to reduce their fossil fuel dependency. Unfortunately, the production of biomass is quite costly and energy intensive, requiring large agricultural areas. Besides its complicated production conditions, until now, the energy efficiency of processes using biomass is generally lower than those using fossil fuels.

LIST OF FIGURES:

LIST OF TABLES

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Appendix A

The following figure describes the average thermal need of the 5 establishments varying with seasons. It represents an annual thermal consumption of about $Q_{th} = 42\ 800\ GJ_{th}$. These results are based on the real heat consumption of the 5 establishments over the past five years.

Figure A.1 Average thermal need

- Natural gas fired heating system:

The heating of the 5 establishments is provided by 25 natural gas boilers with a thermal capacity of 13 MW_{th}, distributed over 13 boiler rooms. For each establishment, the annual heating need and the natural gas consumption of the last five years have been studied to identify the average heat consumption and the global efficiency of the heating system (see Table A.1).

Table A.1
Parameters of the natural gas fired heating system

- Wood fired heating system:

A wood fueled boiler was installed to replace the natural gas heating system. The boiler is connected to a heating network, which transports the heat to the buildings by 3 km long pipes and 13 distribution stations. The boiler consumes about 3 900 tons of wood per year (50% wood waste from sawmills and 50% wood chips). The characteristics of the boiler and the used fuel (see Table A.2) have been the basis for the sensitivity analysis of this paper.

Table A.2
Parameters of the wood fired heating system

Table 1

Parameters of the study

Definition	Item	Unit	Amount	Ref.
Load capacity of truck (ash collection)	$C_1\max^{\uparrow}(a_{\perp}tr)$	kg	7E+3	(Shunping et al., 2010)
Load capacity of truck (wood delivery)	$C_1\max^{\uparrow}(w_{\perp}tr)$	kg	2E+3-50E+3	(Shunping et al., 2010)
Annual distance travelled by the employees[a]	D_e	km	13.2E+3	[-]
Crossed distance to remove ash	d	km	50	[-]
Fuel consumption of passenger car	FC^v	L/km	0.092	(Shunping et al., 2010)
Fuel consumption of truck (wood delivery)	FC^w	L/km	0.168-0.318	(Shunping et al., 2010)
Fuel consumption of truck (ash collection)	FC^a	L/km	0.242	(Shunping et al., 2010)
Average annual heat consumption	Q_{th}	MJ	42.8E+6	Appendix A
Exergy of the produced heat	Ex_{th}	MJ	8.25E+6	Appendix A
Low heating value of diesel	LHV_d	MJ/L	36.5	(Yao, 2010)
Low heating value of dry wood	$LHV_w(0\%)$	MJ/kg	19	(EPA, 2011)
Low heating value of wood	LHV_w	MJ/kg	9.3-13.6	Appendix A
Moisture content of wood	M	w%	0.25-0.45	Appendix A
Ratio of molecular weight of CO_2 to the molecular weight of carbon	$\frac{M_{CO_2}}{M_C}$	[-]	44/12	(EPA, 2005)
Annual consumption of natural gas	Q_{ng}	J	5.2E+13	Appendix A
Ash content of wood	α	[-]	0.02	Appendix A
Ratio of fuel consumption of empty truck to loaded truck (ash collection)	γ^a	[-]	0.75	[-]
Ratio of fuel consumption of empty truck to loaded truck (wood delivery)	γ^w	[-]	0.75	[-]
Oxidation factor of diesel	ε	[-]	0.99	(EPA, 2005)
Efficiency of the wood boiler	η_w	[-]	0.5-0.75	Appendix A
Efficiency of the natural gas boiler	η_{ng}	[-]	0.82	Appendix A
Number of hours worked by the employees[b]	h_w	h	5280	[-]

[a] 5.5 Full Time Employees, 6 months heating period, average daily work commute of 20 km: D_e = 5.5*6*20*20=13.2E+3 km

[b] 5.5 Full Time Employees, 6 months heating period, the number of hours worked by the employees: h_w = 5.5*6*20*8=5270 h

Item	Unit	Amount	Ref.
$EF_{up_{ng}}$	[$kgCO_2$/MJ]	0.01	(ADEME, 2010)
$EF_{comb_{ng}}$	[$kgCO_2$/MJ]	0.05	(ADEME, 2010)
EF_{up_d}	[kgC/L]	0.08	(ADEME, 2010)
EF_{comb_d}	[kgC/L]	0.73	(ADEME, 2010)
$EF_{w_{up}}$	[$kgCO_2$/MJ]	0.0036	(ADEME, 2010)

Table 2

Emission factors

Item	Unit	Solar transformity (sej/unit) [*]Baseline 15.2E+24sej/yr	Deducted from: Ref.
Wood biomass	J	5.62E+4	(Odum, 1996)
Natural gas	J	7.73E+4	(Odum, 1996)
Transport of natural gas[**]	J	1.74E+4	(Romitelli, 2000)
Diesel	J	1.07E+05	(Odum, 2000)
Human labor[**, a]	h	8.58E+13	(Odum, 1996)

Table 3

Solar transformities

[*] Baseline calculated by Brown and Ulgiati (2010).

[**] Different methods exist to calculate transformities of labor and services, notably by using the emergy/money ratio (see Sweeney et al., 2007). In this work, authors used transformities of labor and services which refer to Brazil and the United States because they consider that their economic and technologic levels in this sector are similar to those in France.

[a] Human labor: ((1*131E+16 sej/ind/yr+4.5*28E+16 sej/ind/yr)/5,5)/(24*365)=5,33E+13 sej/h, 5.5 Full Time Employees: 1 Post college+ 4,5 College grad.

Note	Item	Unit	Input	Transformity (sej/unit)	Solar Emergy (sej)
	Nonrenewable Inputs				
1	Natural gas	J	5.2E+13	7.73E+4[a]	4.02E+18
	Goods and services				
2	Transport of natural gas	J	5.2E+13	1.74E+4[b]	9.04E+17
	Annual product yield (exergy)	J	8.25E+12	5.96E+05[c]	4.92E+18

Table 4

Emergy flows of the natural gas fired heating system (parameters are given in Table 1)

[a] Transformity of natural gas (see Table 3)

[b] Transformity of natural gas transport (see Table 3)

[c] Deducted transformity of the heat produced by the heating system.

Note	Item	Unit	Input	Transformity (sej/unit)	Solar Emergy (sej)
	Nonrenewable Inputs				
1 *	Wood transportation (0 km)	J	0	1.07E+5[a]	0
1 *	Wood transportation (50 km)	J	3.6E+11	1.07E+5	3.84E+16
1 *	Wood transportation $\left(D_{\max}^{s}\right)$	J	7.14E+12	1.07E+5	7.61E+17

Table 5

Emergy flows of the wood fired heating system (LHV_w = 11.49 MJ, η_w =0.65 and $C_1\max^{\uparrow}(w_1 tr)$ =14 t)

1 *	Wood transportation (D_{max}^{cf})	J	3.57E+13	1.07E+5	3.8E+18
2	Ash collection	J	1.03E+10	1.07E+5	1.09E+15
3	Commute of the employees	J	4.43E+10	1.07E+5	4.72E+15
Note	Item	Unit	Input	Emission factor ($kgCO_2$/unit)	CO_2 emission ($kgCO_2$)
	Nonrenewable Inputs				
5	Human labor	h	5280	8.58E+13[c]	4.53E+17
	Annual product yield (0 km) (exergy)	J	8.25E+12	5.04E+05**	4.16E+18
	Annual product yield (50 km) (exergy)	J	8.25E+12	5.09E+05**	4.2E+18
	Annual product yield (D_{max}^{E}) (exergy)	J	8.25E+12	5.96E+05**	4.92E+18
	Annual product yield (D_{max}^{cf}) (exergy)	J	8.25E+12	9.65E+05**	7.97E+18

* The emergy flow of wood transportation depends on the supply distance of wood , the values represent the emergy flows of wood transportation for a supply distance of respectively 0 km (direct supply), 50 km, D_{max}^{E} = 990 km and D_{max}^{cf} = 4950 km.

[a] Transformity of diesel (see Table 3)

[b] Transformity of wood biomass (see Table 3)

[c] Transformity of human labor (see Table 3)

** Deducted transformity of the heat, produced by the heating system, for a supply distance of respectively 0 km (direct supply), 50 km, D_{max}^{E} = 990 km and D_{max}^{cf} = 4950 km.

Table 6

CO_2 emissions from the natural gas fired heating system (parameters are given in Table 1)

Note	Item	Unit	Input	Emission factor ($kgCO_2$/unit)	CO_2 emission ($kgCO_2$)
1	Natural gas	J	5.2E+13	5E-8[a]	2.60E+06
	Goods and services				
2	Transport of natural gas	J	5.2E+13	1E-8[b]	5.20E+05
	Annual product yield (exergy)		8.25E+12	3.78E-07[c]	3.12E+06

[a] Emission factor of natural gas combustion (see Table 2)

[b] Upstream emission factor of natural gas (see Table 2)

[c] Deducted emission factor of the heating system.

Table 7

	Nonrenewable Inputs				
1 *	Wood transportation (0 km)	L	0	2.94[a]	0
1 *	Wood transportation (50 km)	L	9.88E+03	2.94	2.91E+04
1 *	Wood transportation (D_{max}^{E})	L	1.96E+05	2.94	5.75E+05
1 *	Wood transportation (D_{max}^{cf})	L	9.79E+05	2.94	2.88E+06
2	Ash collection	L	2.82E+02	2.94	8.28E+02
3	Commute of the employees	L	1.21E+03	2.94	3.57E+03
	Renewable Inputs				
4	Wood biomass	J	6.59E+13	3.6E-9[b]	2.37E+05
	***Annual product yield (0 km) (exergy)**	J	8.25E+12	2.93E-08**	2.41E+05
	***Annual product yield (50 km) (exergy)**	J	8.25E+12	3.28E-08**	2.71E+05
	***Annual product yield (D_{max}^{E}) (exergy)**	J	8.25E+12	9.90E-08**	8.17E+05
	***Annual product yield (D_{max}^{cf}) (exergy)**	J	8.25E+12	3.78E-07**	3.12E+06

CO_2 emissions from the wood fired heating system (LHV_w = 11.49 MJ, η_w =0.65 and $C_{max}(w_{tr})$ =14 t)

*The CO_2 emissions of wood transportation depend on the supply distance of wood , the values represent the CO_2 emissions of wood transportation for a supply distance of respectively 0 km (direct supply), 50 km, D_{max}^{E} = 990 km and D_{max}^{cf} = 4950 km.

[a] Emission factor of diesel per [kgCO_2/L]

[b] Upstream emission factor of wood biomass (see Table 2)

** Deducted emission factor of the heating system, for a supply distance of respectively 0 km (direct supply), 50 km, D_{max}^{E} = 990 km and D_{max}^{cf} = 4950 km.

Table 8

Relative errors of emission factors

Relative error	Value
$\sigma_{EF_{ng}}$	1.08E-01
$\sigma_{EF_{d}}$	9.10E-02
$\sigma_{EF_{w}}$	8.24E-03

Table 9

Relative errors of transformities

Relative error	**Value**
$\sigma_{\tau_{ng}}$	6.46E-01
$\sigma_{\tau_{d}}$	9.16E-02
$\sigma_{\tau_{w}}$	4.86E-01
$\sigma_{\tau_{kl}}$	5.95E-02

Table A.1

Parameters of the natural gas fired heating system

[a] The total heat production of the system is about 4.28E+13 J, using a Carnot efficiency of 0.19 (ambient temperature is 20°C and temperature of hot water is 90°C) the exergy of the produced heat is 8.25E+12 J.

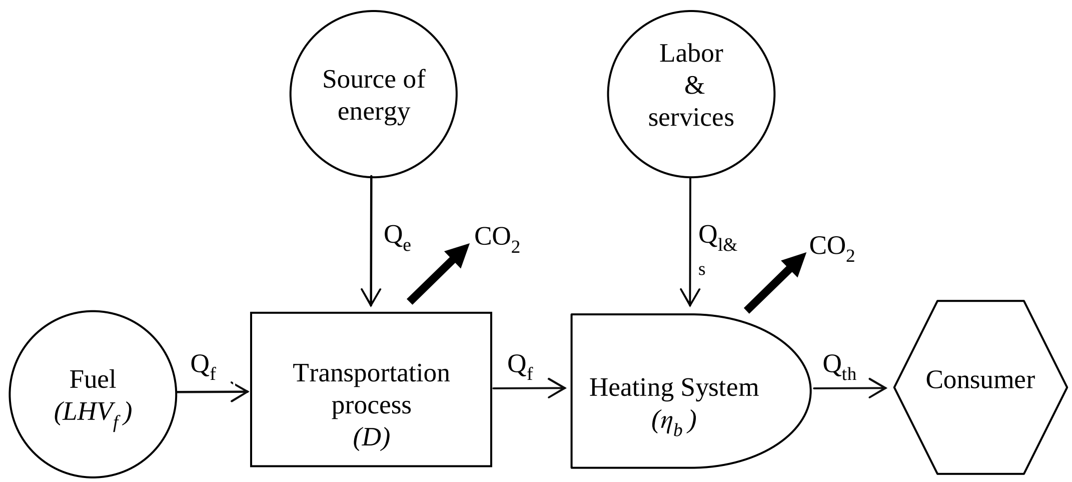
Definition	Item	Unit	Amount
Average annual heat consumption	Q_{th}	MJ	42.8E+6
Exergy of produced heat [a]	Ex_{th}	MJ	8.25E+6
Average annual natural gas consumption	Q_{ng}	MJ	5.2E+7
Global efficiency of the heating system	η_{ng}	-	0.82

Table A.2

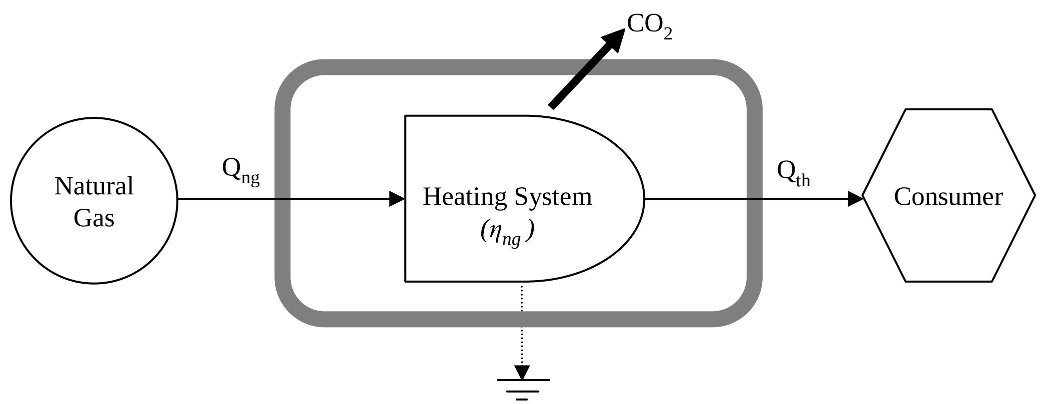
Low heating value of wood	LHV_w	MJ/kg	11.5
Moisture content of wood	M	w%	35
Ash content of wood	α	-	0.02
Global efficiency of the heating system	η_w	-	0.65
Social impact	-	-	5.5 Full Time Employee[a]

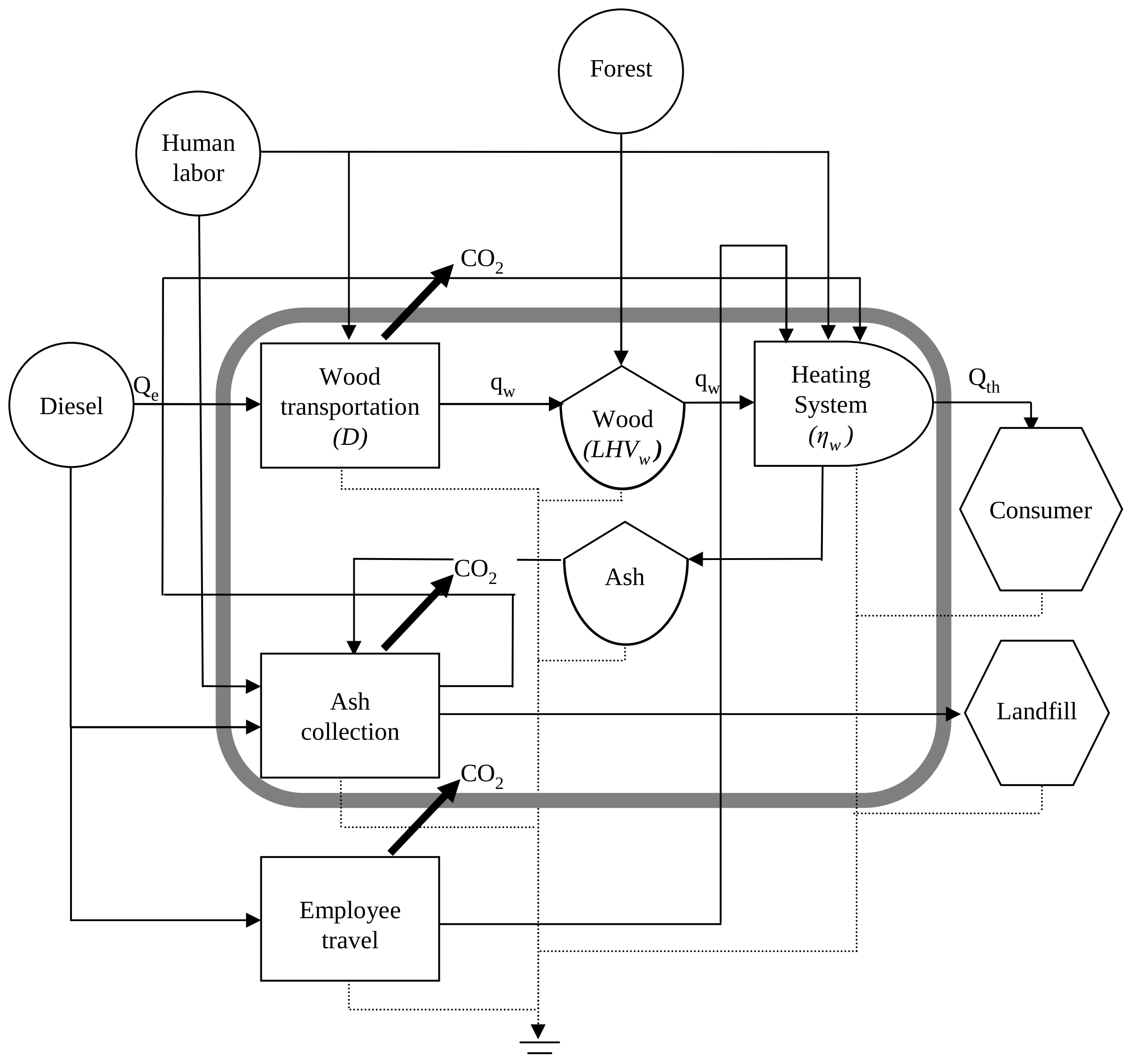
Parameters of the wood fired heating system

[a] 1 Post college+ 4,5 College grad.

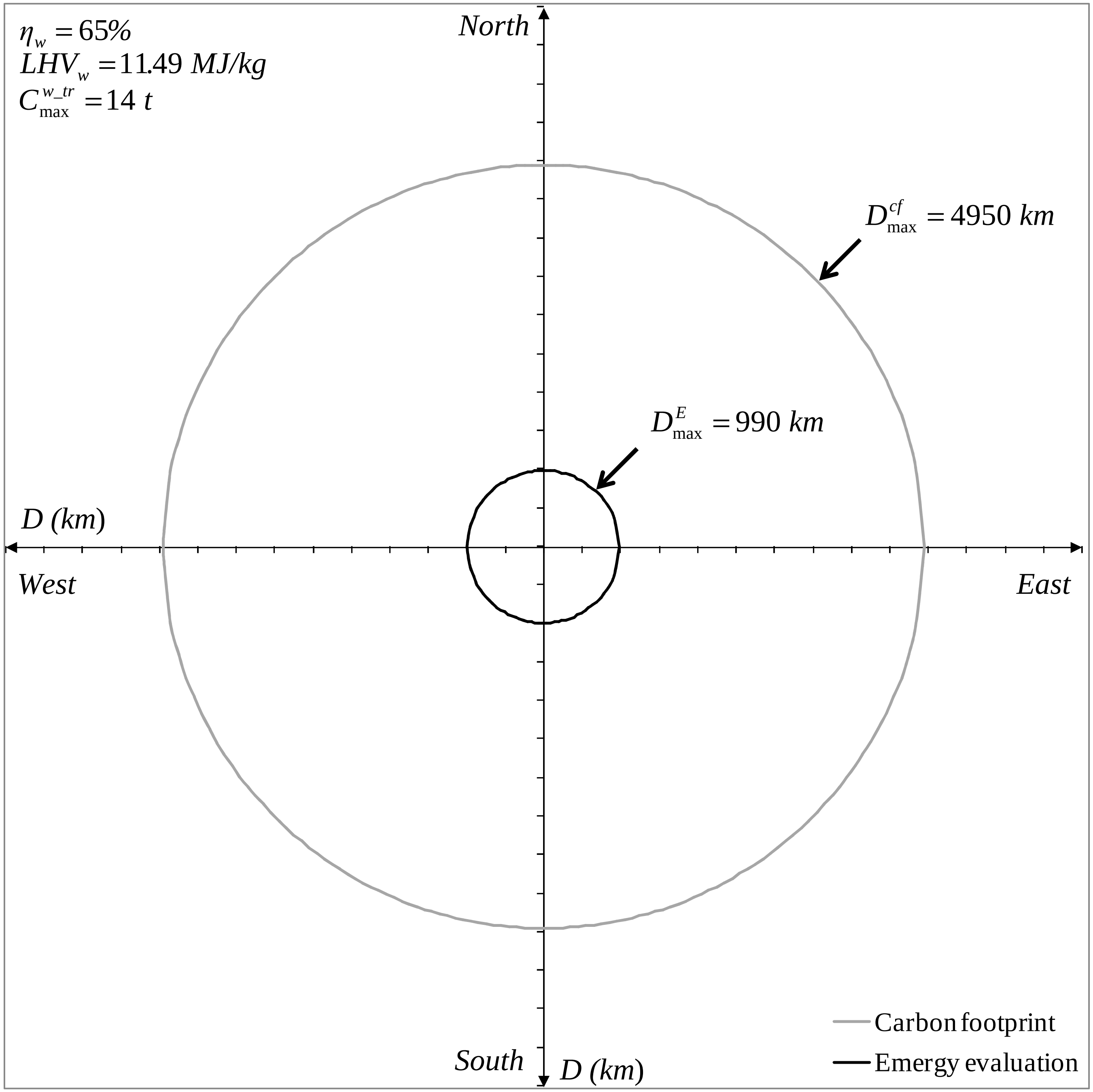


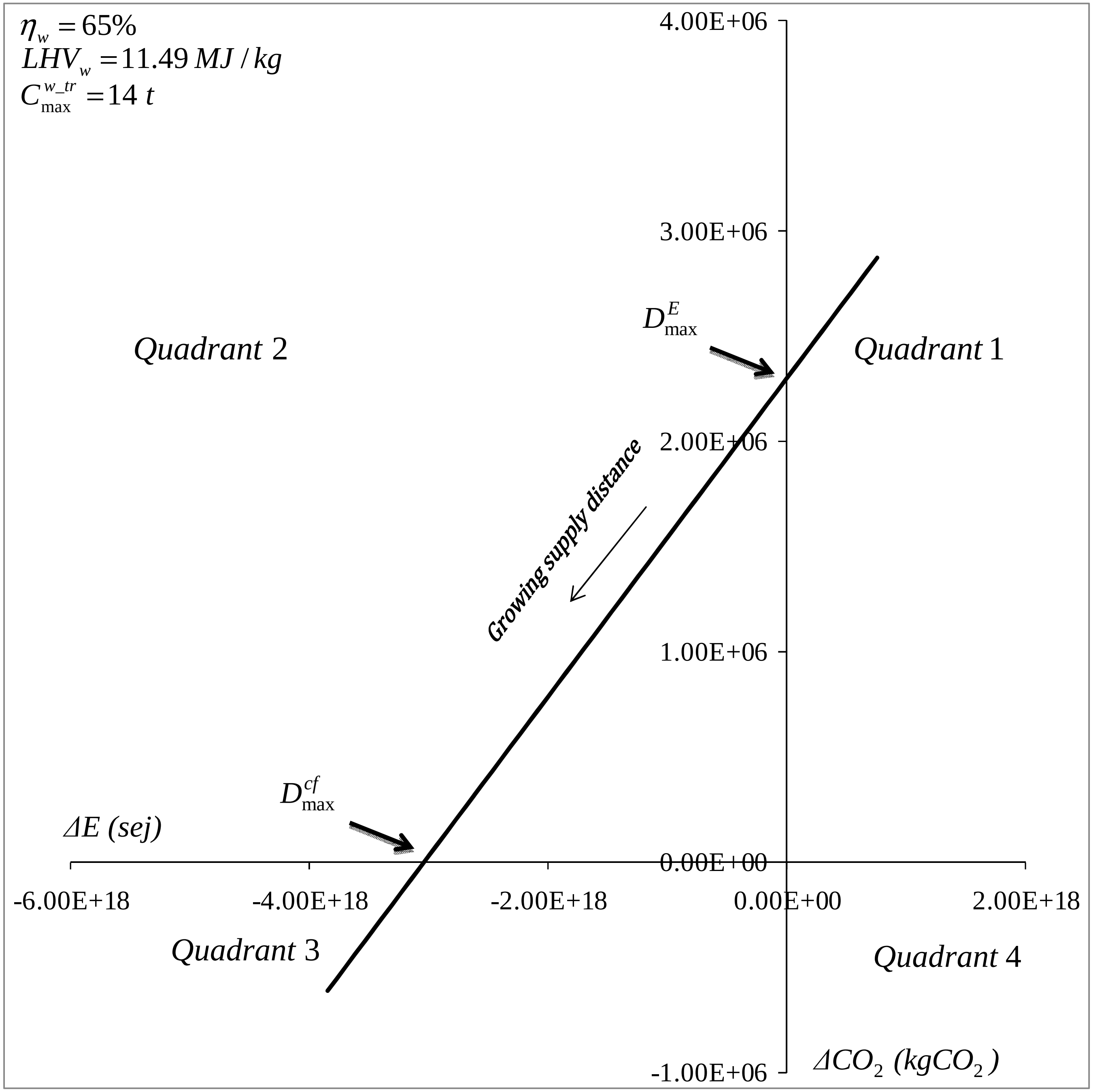
Source of energy
Labor & services
Q_e
CO2
Q_l&s
CO2
Fuel
(LHV_f)
Q_f
Transportation process
(D)
Q_f
Heating System
(η_b)
Q_th
Consumer


CO2
Natural
Gas
Qng
Heating System
(ηng)
Qth
Consumer

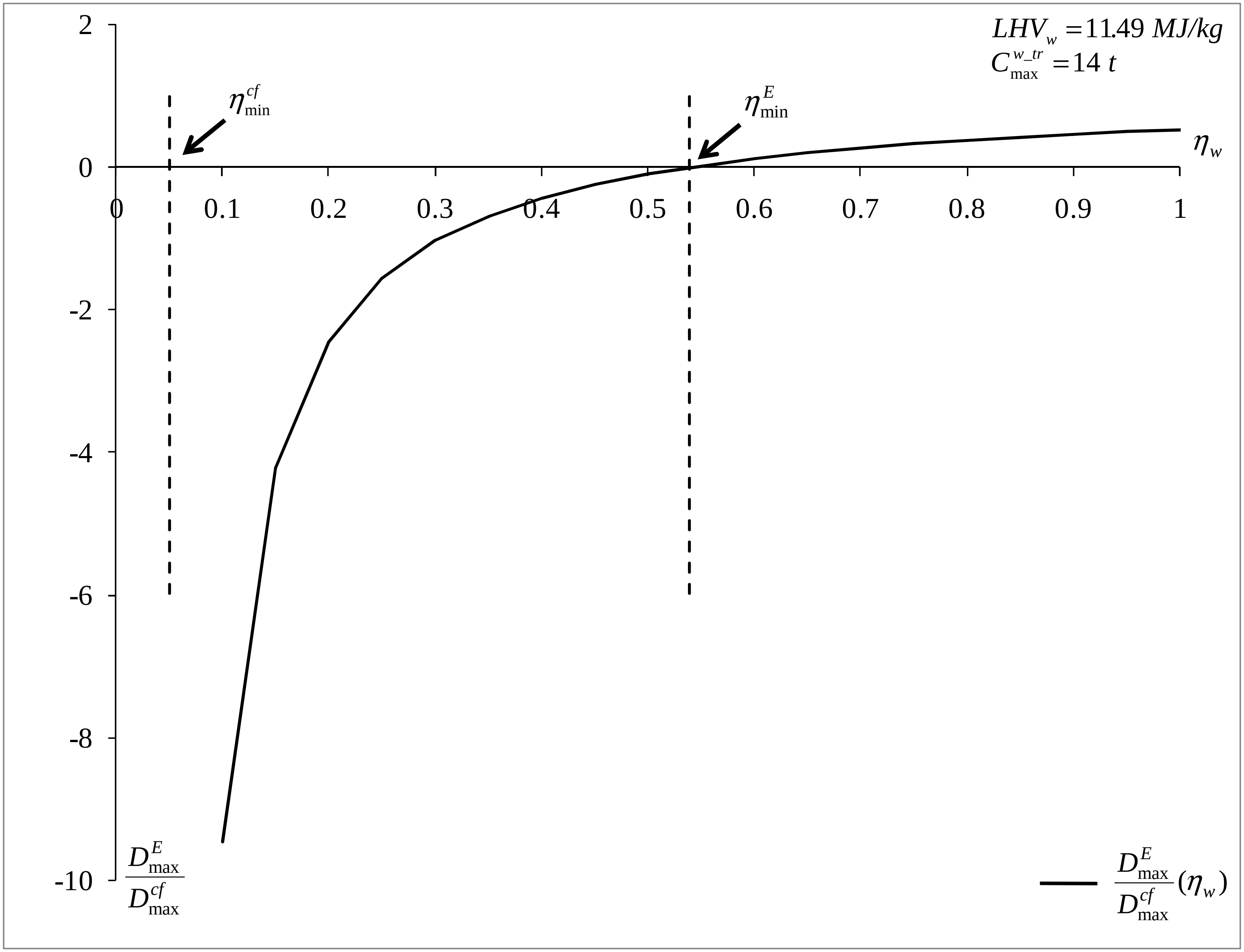


Forest
Human labor
CO2
Diesel
Qe
Wood transportation (D)
qw
Wood (LHVw)
qw
Heating System (ηw)
Qth
Consumer
CO2
Ash
Ash collection
Landfill
CO2
Employee travel

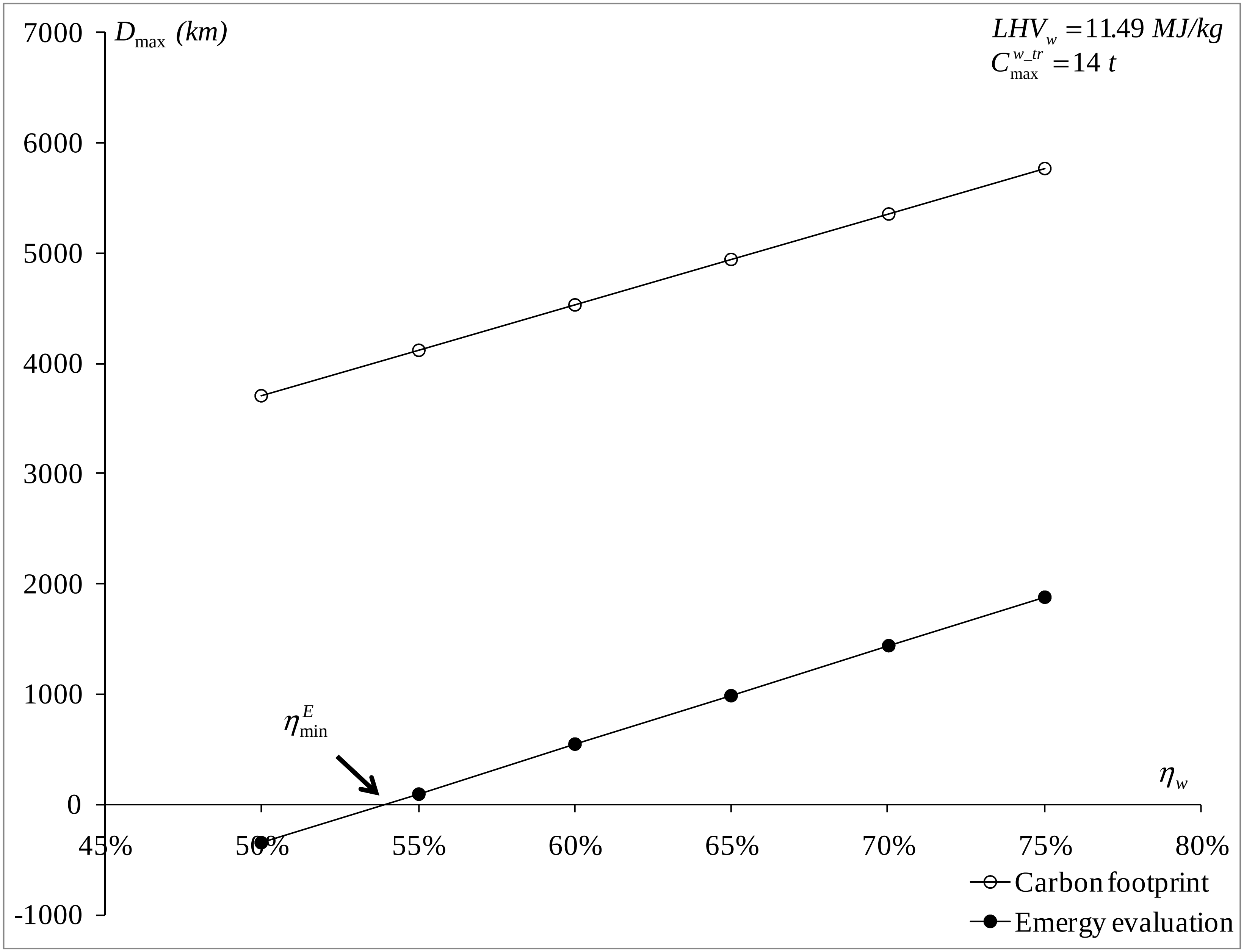

$\eta_w = 65\%$
$LHV_w = 11.49\ MJ/kg$
$C_{\max}^{w\_tr} = 14\ t$
North
$D_{\max}^{cf} = 4950\ km$
$D_{\max}^{E} = 990\ km$
D (km)
West
East
South
D (km)
Carbon footprint
Emergy evaluation



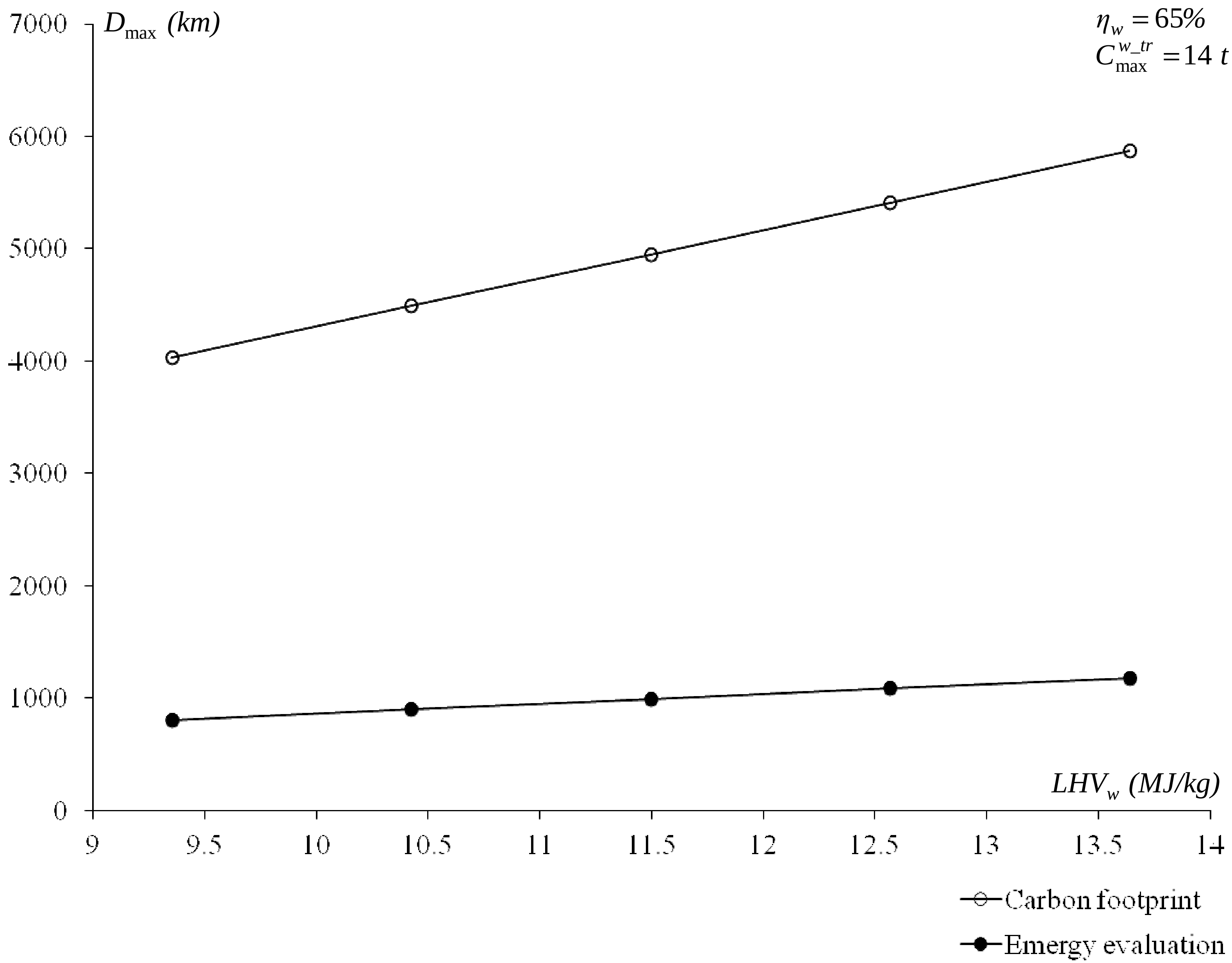
$\eta_w = 65\%$
$LHV_w = 11.49\ MJ/kg$
$C_{\max}^{w\_tr} = 14\ t$
4.00E+06
3.00E+06
2.00E+06
1.00E+06
0.00E+00
-1.00E+06
$D_{\max}^{E}$
Quadrant 1
Quadrant 2
Quadrant 3
Quadrant 4
Growing supply distance
$D_{\max}^{cf}$
ΔE (sej)
-6.00E+18
-4.00E+18
-2.00E+18
0.00E+00
2.00E+18
ΔCO_2 ($kgCO_2$)



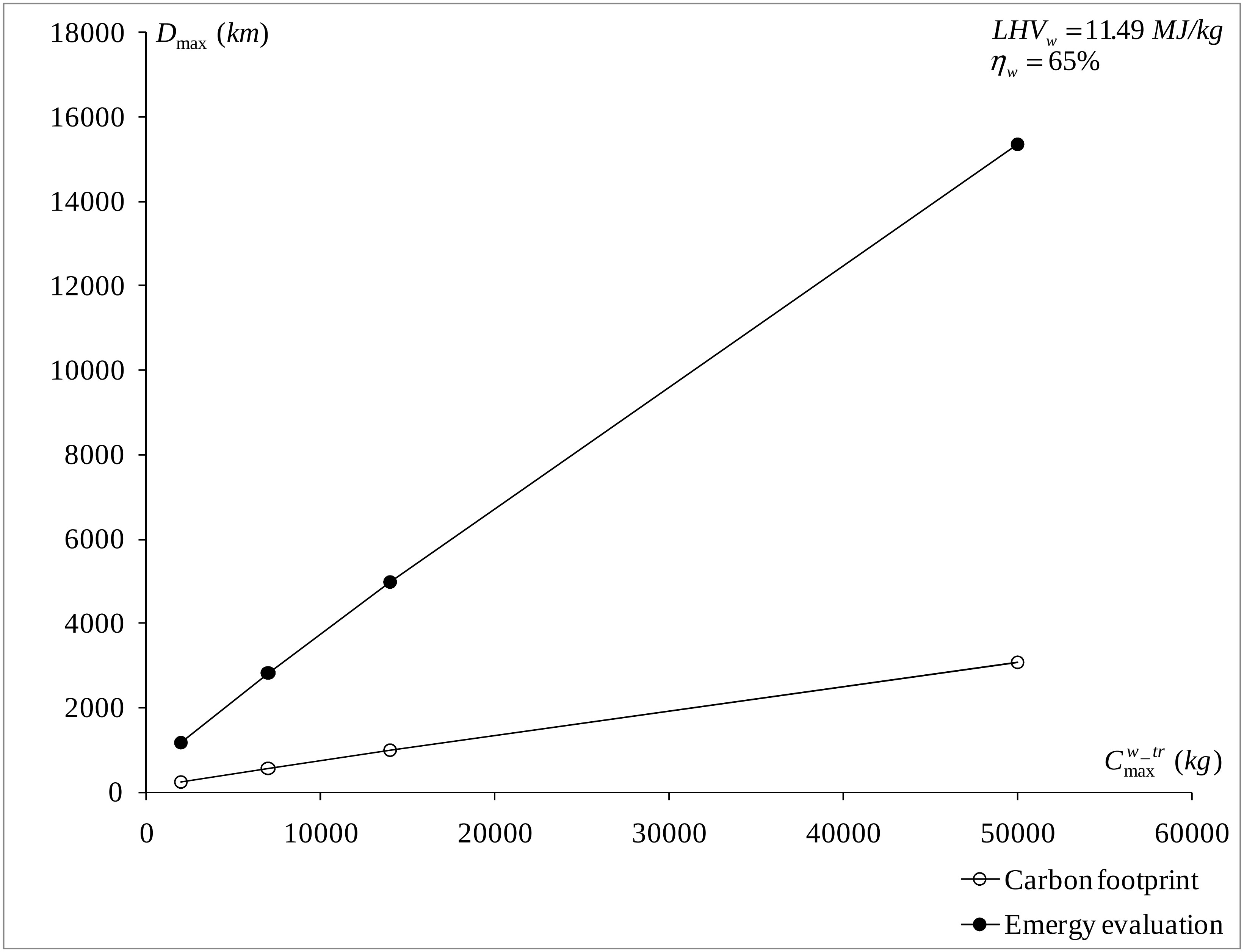
$LHV_w = 11.49\ MJ/kg$
$C_{\max}^{w\_tr} = 14\ t$
$\eta_{\min}^{cf}$
$\eta_{\min}^{E}$
η_w
2
0
-2
-4
-6
-8
-10
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
$\frac{D_{\max}^{E}}{D_{\max}^{cf}}$
$\frac{D_{\max}^{E}}{D_{\max}^{cf}}(\eta_w)$



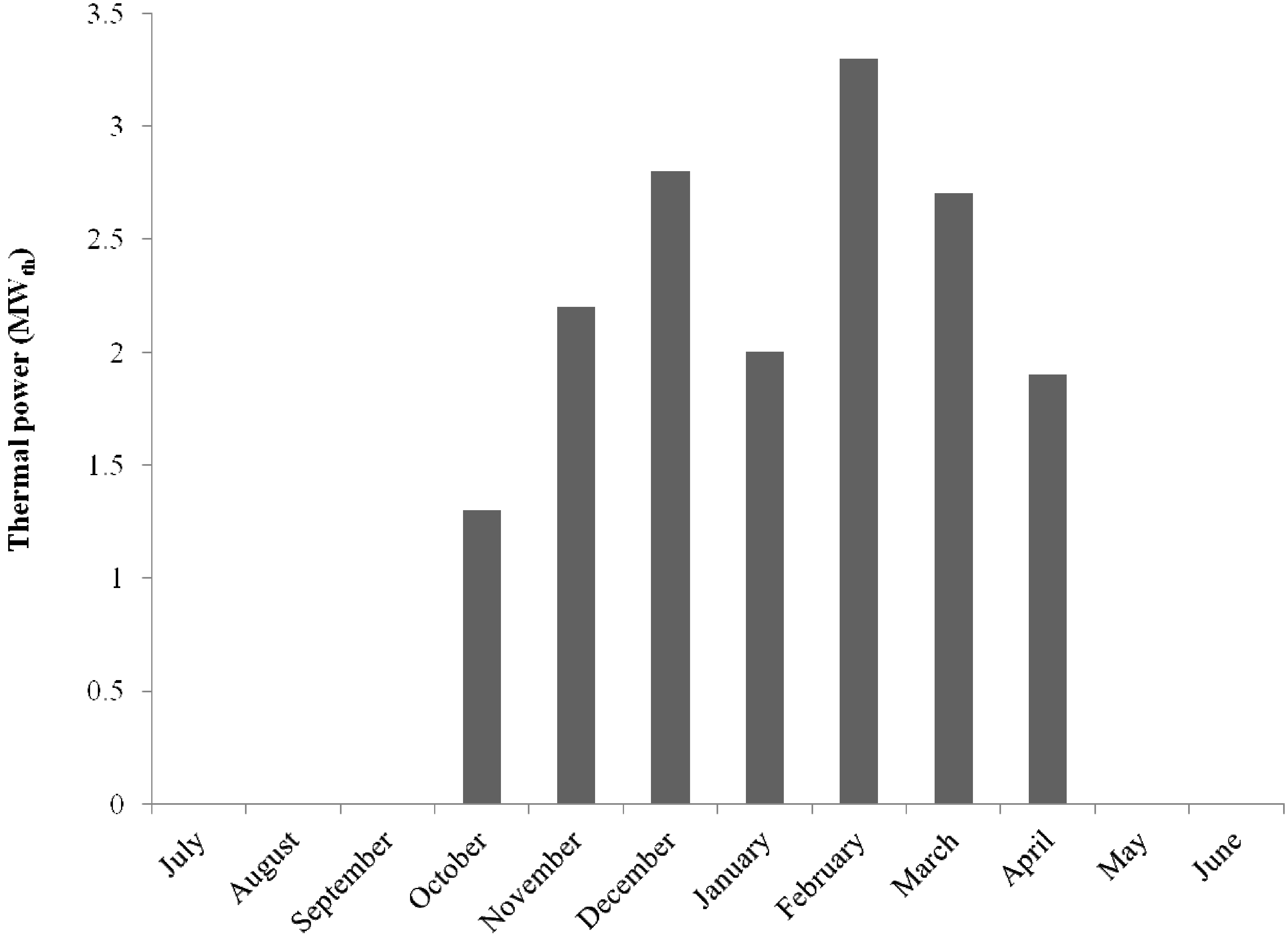
$D_{\max}$ (km)
$LHV_w = 11.49$ MJ/kg
$C_{\max}^{w\_tr} = 14$ t
7000
6000
5000
4000
3000
2000
1000
0
-1000
$\eta_{\min}^{E}$
η_w
45%
50%
55%
60%
65%
70%
75%
80%
Carbon footprint
Emergy evaluation



D_{max} (km)
$\eta_w = 65\%$
$C_{max}^{w\_tr} = 14\ t$
7000
6000
5000
4000
3000
2000
1000
0
9
9.5
10
10.5
11
11.5
12
12.5
13
13.5
14
LHV_w (MJ/kg)
Carbon footprint
Emergy evaluation



$D_{\max}$ (km)
$LHV_w = 11.49$ MJ/kg
$\eta_w = 65\%$
18000
16000
14000
12000
10000
8000
6000
4000
2000
0
0
10000
20000
30000
40000
50000
60000
$C_{\max}^{w\_tr}$ (kg)
Carbon footprint
Emergy evaluation


Thermal power (MW$_{th}$)
0
0.5
1
1.5
2
2.5
3
3.5
July
August
September
October
November
December
January
February
March
April
May
June